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Review

Revitalizing operational reliability of the electrical energy system in Libya: Feasibility analysis of solar generation in local communities

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ABSTRACT

The political upheaval and the civil war in Libya had a painful toll on the operational reliability of the electric energy supply system. With frequent power cuts and crumbling infrastructure, mainly due to the damage inflicted upon several power plants and grid assets as well as the lack of maintenance, many Libyans are left without electricity for several hours a day. As the country has a staggeringly immense potential of solar energy, it is inevitable to exploit such potential, to avert system-wide blackouts. This paper investigates the use of small-scale PV systems in local communities as non-wires alternative (NWA), offering excess energy exchange within local/neighboring microgrids (MGs) for reliable electric power supply. Different combinations of PV/storage/diesel distributed generations (DGs), with grid-interface options, were applied on a case study of a typical dwelling in the Eastern Libyan city of Benghazi. Technical and financial feasibility assessments were carried out to contrast between various supply combinations. Sensitivity analysis of the PV-grid system was also conducted using Net Present Value (NPV) and the payback time indicators to determine the impacts of Feed-in Tariff (FiT) rates, financial incentives, electricity tariff, and inflation rate on the economic viability of the PV grid system. Results show that the PV-grid system has a promising potential under reasonable set of varying system parameters. On top of its social and environmental-friendly advantages, the PV-battery system is found to be more economical when adopted as a standalone NWA solution as compared to the diesel generator option, even at the lowest diesel price. The PV-grid system does not only provide a short-term remedy to the rolling blackouts in Libya but also enhances system operational reliability by providing a NWA to rundown or shattered grid infrastructure, thus bolstering energy provision in residential neighborhoods.

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List of abbreviations

Ah	Ampere-hour
B	Billion
CO_2	Carbon dioxide
CSERS	Center for Solar Energy Research and Studies
CBL	Central Bank of Libya
CNY	Chinese Yuan
CC	combined cycle
CCGT	combined cycle gas turbines
COE	cost of energy
DG	distributed generation
EIA	Energy Information Administration
EGP	Egyptian Pound
ESS	Energy storage system
FiT	Feed-in Tariff
GW	Gigawatt
GECOL	General Electricity Company of Libya
GHI	Global horizontal irradiation
GoL	Government of Libya
GHG	greenhouse gas
GCPV	grid-connected photovoltaic
GDP	gross domestic product
HOMER	Hybrid Optimization Model for Electric Renewables
kWh	kilowatt hour
kW	kilowatt
LD	Libyan Dinar
RM	Malaysian Ringgit
MW	megawatt
MGs	microgrids
NASA	National Aeronautics and Space Administration
NWA	non-wires alternative
NPC	net present cost
NPV	net present value
O&M	operation & maintenance
PV	photovoltaic
REAoL	Renewable Energy Authority of Libya
RE	renewable energy
km^2	square kilometer
T&D	transmission and distribution
TWh	terawatt hour

1. Introduction

Libya is a Mediterranean country located in North Africa between latitudes 20° N and 32° N and between 10° E and 25° E longitudes, as shown in Fig. 1. In the northern part of the country, summer average temperatures range from 27 °C to 32 °C. In the southern part (desert), temperature ranges between 40 °C and 46 °C, while in winter it ranges from −1 °C to 12 °C. Libya extends over a land area of about 1.76×10^6 km^2, with a population and population growth rate of 6.3 million and 1.4% respectively, as reported in the year 2015 (WA, 2019).

Libya is blessed with abundant gas and oil resources. It has large quantities of indigenous oil supplies, which is currently the largest in Africa and the ninth-largest globally; with 48 B barrels of proven

Fig. 1. Geopolitical map of Libya (UN, 2015).

crude oil reserves (Bindra et al., 2015). The proven natural gas reserves stand at 158 B cubic feet (EIA, 2019a). Inasmuch as the Libyan political economy was dominated by oil, not surprisingly, the electricity supply industry in the petro-state depends entirely on conventional power generation using fossil fuels. Generally speaking, the electrical energy supply and provision enterprise performed reasonably well in Libya, before 2011, with the installed generation capacity superseding load demand with an adequate margin.

Following the Arab spring protests in 2011, Libya had a full-fledged revolt against its reigning political regime; leading eventually to its downfall. However, the country has descended into civil war since then, with frequent infighting using heavy weaponry. The continuation of such crisis until this very day poses significant challenges to the power grid infrastructure.

Libya has suffered severe electricity shortages and power cuts in the past few years. This is basically due to the damage and destruction incurred, during the war, as well as sabotage and vandalism on some of its power plants and transmission network assets; particularly in eastern and western Libya. The situation was further aggravated by the lack of cash and foreign companies to undertake maintenance and complete suspended projects. With actual electricity generation below load demand, grid system operators were left with no option but to implement rolling blackouts to avoid system-wide collapse. Although some homeowners, businesses, and health centers have tended towards using mobile diesel generators, many Libyans are still left out with no access to grid electricity supply few hours a day.

On the other hand, it has been estimated that every year, each 1 km^2 of desert in the Middle East/North Africa region receives solar energy equivalent to 1.5 million barrels of crude oil (Ahmed et al., 2013), and from each km^2 of desert land, up to 250 GWh of electricity can be harvested each year (DESERTEC, 2007). As Libya is located on the cancer orbit line in the middle of North Africa, it is exposed to the sun rays throughout the year with long hours during the day exceeding 7.2 of average GHI in the south (Belgasim et al., 2018). If only a tiny fraction of the massive solar energy potential in Libya could be harnessed, not only its own energy demand could be met but also could contribute significant part to the world energy demand by exporting electricity (Hans and Franz, 2009).

Since solar energy potential in Libya is well established beyond doubt, this paper, different to other publications, is not concerned with exploring solar energy prospects or urging the GoL to draft national plans to facilitate the adoption of solar energy on a large scale. On the contrary, this paper advocates the use of small-scale solar PV energy systems in small local communities, comprising MGs, to counter the damage suffered by critical power grid infrastructure and cater for the electricity needs of end customers in a modular fashion. This can revitalize the reliability of the existing grid system and boost energy provision in the conflict-torn country. Once the grid is fully restored, the excess clean energy harvested from the NWA solar PV energy systems of local communities can then be sold back to the grid through an appropriate energy policy mechanism.

The remainder of this paper is organized as follows; section 2 diagnoses the issue of electricity deficiency by reviewing the current state of the electrical energy system in the country. A recent field survey concerning the status of electric power generation plants is also provided. The potential of solar energy in Libya along with its applications and related research studies are discussed in section 3. The concept of NWA solution to cater for electricity shortage is elaborated in section 4. Section 5 defines the FiT policy and provides some successful international experiences. Based on actual average daily energy consumption, a case study of a PV system representing a NWA designed for a typical house located in Benghazi is presented in section 6. The economic analysis model is introduced in section 7. Feasibility results of the grid-interfaced NWA system for different hybrid energy system combinations as well as sensitivities of diesel fuel price, electricity tariff, storage capacity, FiT rates, inflation, interest rate, and financial incentives are analyzed in section 8. Finally, section 9 concludes the paper.

2. Current state of electrical energy supply system in Libya

The Libyan economy and energy sector are still heavily dependent on fossil fuels. In fact, hydrocarbons account for over 65% of the country's GDP and 96% of the national revenue (El-Fadli, 2012). However, oil prices are fluctuating subject to demand and future commodities market resulting in an annual budget deficit and hence an inflation (Lyu et al., 2020). Oil prices were below \$20 per barrel prior to the year 2000, then saw an upward trend to nearly \$75 in the third quarter of 2006, and skyrocketed to \$147 by mid-2008. The price again rose to \$112 in 2011, and thereafter fell gradually to reach its lowest level at \$22.5 during the 1st quarter of 2016; then settling above \$40 in the third quarter of the same year (OPEC, 2016). The average closing prices approached \$60 a barrel in 2019. Amid a continuing rise in the oil surplus in the spot market and accumulating unsold shipments, the year 2020 has seen unpredictable price fluctuations due to the COVID-19 outbreak. For example, OPEC's Reference Basket has dropped by 48%, month-on-month, to stand at \$17.66, recording the lowest monthly point since December 2001 (OPEC, 2020). However, a forecast by U.S. EIA anticipates a high oil price case of around \$212 per barrel by 2050 (EIA, 2019b).

Presently, Libya generates almost all of its electrical energy using fossil-fueled power plants to satisfy its growing demand for electricity (Zaroug, 2013). GECOL is the state-owned vertically integrated utility responsible for generation, transmission, distribution, operation, and control of the electric power grid system as well as water desalination plants (Alsuessi, 2015). One of the main challenges encountered while writing this paper was the data collection. Affected by the ongoing political unrest, GECOL has not been publishing any annual reports since 2010. In order to come up with updated and reliable information regarding the electrical energy situation in the country, the authors have utilized a combination of different research techniques including field work and interviews with various senior managerial levels in direct relation to the energy sector in Libya. Table 1 describes the up-to-date status of the electrical power generation plants in Libya. As can be noticed, the nominal capacity of existing power plants is about 14,500 MW whereas the available full generation capacity could hardly reach 6,320 MW only; of which around 63% is generated by natural gas and 37% run by oil. Based on technology, main gas turbines contribute 39.3% in electricity production, CCGT accounts for 37%; 10.6% comes from steam turbines, whereas small gas units cover the remainder. According to our field survey, the 2019 peak summer load hit 7,500 MW, while the peak winter load reached 7,200 MW. These values show that there is about 1,200 MW of generation deficit.

The electricity sector is definitely a key area that needs to be addressed since the country has been regularly hit by widespread blackouts (Mohamed et al., 2016). This is because the power generation is well below peak electricity demand resulting in shortfalls. Retirement and decommissioning of some generators along with the damage sustained by several power plants during the 2011 war, as well as the blockade imposed by rival militia factions on Libyan oil fields and refineries are the main reasons for electricity shortages. Specifically, the network in the eastern part of Libya has suffered from massive destruction, mainly in the major power substations. In addition, loss of the interconnection between the

Table 1
Status of electrical power plants in Libya as of January 2020.

Power plant	Phases	Generation Units		Rated Capacity per Unit (MW)	Date of Operation and Status	Current Output (MW)
Al Khums	Phase 1	4	Steam	127	1982	400
	Phase 2	4	Gas	150	1995	560
	Phase 3	2	Gas	275	2017–out of service	0
North Benghazi	Phase 1	4	Steam	40	1979-out of service	0
	Phase 2	3	Gas	150	1995	240
	Phase 3	1	Gas	165	2002	75
		2	CC	150	2007	0
	Phase 4	2	Gas	285	2009	500
		1	CC	250	2012	0
Al Zawiya	Phase 1	4	Gas	165	2000	575
	Phase 2	2	Gas	165	2005	270
	Phase 3	3	CC	150	2007	185
	Phase 4	2	Gas	25	2014	45
Misrata CC	Phase 1	2	Gas	285	2010	530
	Phase 2	1	CC	250	2013	225
South Tripoli	Phase 1	5	Gas	100	1994	330
	Phase 2	2	Gas	47	2016	0
Sarir	Phase 1	2	Gas	285	2010	400
	Phase 2	1	Gas	285	2013	
Zwitina CC	Phase 1	4	Gas	50	1994	90
	Phase 2	2	Gas	285	2010	500
		1	CC	250	Suspended	0
Al Jabal Algharbi- Ruwais	Phase 1	2	Gas	156	2005	785
	Phase 2	2	Gas	156	2006	
	Phase 3	1	Gas	156	2010	
	Phase 4	1	Gas	156	2012	
West Tripoli	Phase 1	5	Steam	65	1976-out of service	0
	Phase 2	2	Steam	120	1980- out of service	0
	Phase 3	4	Steam	350	Contracted	0
	Phase 4	3	Gas	25	2014	60
Darna	Phase 1	5	Steam	65	1985	0
Tubruk	Phase 1	5	Steam	65	1985	0
Alkhalij-Sert	Phase 1	4	Steam	350	2014 (1 unit in operation)	280
Alzahra	Phase 1	2	Gas	15	1971	0
	Phase 2	4	Gas	47	Under Construction	0
Ubari	Phase 1	4	Gas	165	2019	240
Abu Kammash	Phase 1	6	Gas	15	1982	0
Zliten	Phase 1	3	Gas	15	1975	0
Alfurnaj	Phase 1	2	Gas	15	1971	10
Lamluda	Phase 1	1	Gas	33	1975	0
Alkufrah	Phase 1	3	Gas	25	1975	0
Misrata Kerzaz	Phase 1	3	Gas	15	1984	20

North Benghazi electric power plant and other major power plants such as Zwitina, Sarir, and western plants has affected the stability and reliability in all parts of the network, particularly the eastern electric network. The recent military escalation that has been taking place in and around Tripoli has enormously affected the transmission grid infrastructure, coupled with vandalism of grid components, resulting in more than 10 h a day of power cuts in many regions in the west of the country. Electricity shortage was relatively reduced by importing electricity from neighboring countries as well as renting MW-scale diesel generators. While diesel generators can be considered as a provisional remedy, they provide temporary, yet uneconomic and environmentally unfriendly, solution to a chronic problem.

The Libyan historical load profile data show that the maximum power occurs during the summer season and the residential sector represents the highest share in electrical energy demand followed by the commercial and industrial sectors, as presented in Fig. 2 (REAoL, 2012). It is worth mentioning that the 23% share shown in the figure is attributed largely to squatter communities and businesses that were displaced and uncontrollably spread out during the last few years, due to unstable political environment. Based on GECOL's last official annual report, electricity demand in the country increased by 12% yearly between 2003 and 2010 (GECOL, 2012; Sahati, 2014). If this pattern continues, electricity

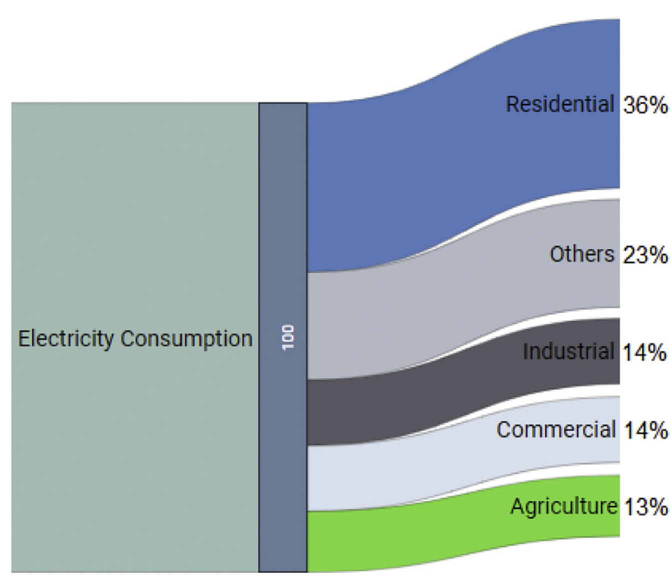


Fig. 2. Sankey diagram of electricity consumption per sector (GECOL, 2012).

demand would strike at around 14 GW by 2030. Therefore, the investment in new power plants is crucial. As can be seen from Table 1, the power plants which were under construction prior to the civil war remain, however, suspended due to the very high risk associated with adverse business climate of the war-torn country.

Similarly, most of the Libyan electric network is concentrated on the coast, where most of the inhabitants live. The transmission system is completely interconnected nationally and regionally to ensure both reliability and security. The Libyan electric transmission line network consists of 13,706 km of 220 kV. In addition, around 2,422 km were upgraded to 400 kV to cope with the increasing load-growth (Salah et al., 2014). Fig. 3 depicts the high voltage transmission network. As stated earlier, Libya's national electricity grid was one of the primary infrastructures which experienced a significant damage during the civil war and militia attacks. The network incurred an estimated damage worth of $1.0 B in over 300 substations. Furthermore, about 2,000 km of power lines, and 6,000 km of distribution lines had been destroyed (BMI, 2013). Whilst repairs have been taking place on the electricity infrastructure since 2011, a number of power generation units and substations are still out of service.

At the same time, the main emitters of CO_2 are fuel combustion in the power generation sector which contributes 60 million tonnes of the GHG emissions (Ekhlat et al., 2007). Reflected by a high per capita energy consumption, CO_2 emissions (metric tons per capita) in Libya stood at 8.73 in 2018. This is high as compared for instance to a large industrial country like China, which had an emission level of 7.5 (EC, 2019). However, in order to maintain meeting the growing electrical energy demand and achieve a sustainable economic growth, GoL established the REAoL in 2007 to promote RE use as well as to integrate RE technologies into the energy supply mix.

3. Solar energy potential in Libya

Industrialization and population rise in developing countries have, globally speaking, increased the demand for electrical energy drastically (Fasihi and Breyer, 2020). On the supply side, oil prices had a significant plunge in 2014 due to excess supply and continued to fluctuate since then due to, from a global perspective, political instability in the Middle East and the recent nation-wide lockdowns due to Covid-19 pandemic. On the other hand, fossil fuels are ultimately depletable and have problems that are squarely associated with global warming (Shao et al., 2020; Wamsler et al., 2020). These factors have prompted the research and implementations of RE resources to become more urgent (Jurasz et al., 2020).

On a global basis, the share of RE in global power capacity grew to over 33% in 2018, the largest annual increase ever with an estimated 181 GW of new installations; boosting the cumulative global capacity of RE sources (excluding hydro) to 2,400 GW (REN21, 2019). In Germany, RE sources delivered about 38% of the total net power consumption in 2017 (24% in 2012), on the way to meet its national target of 50% in 2030, and 80% in 2050 (Cherp et al., 2017). The cumulative installed solar PV capacity in Germany reached 25 GW in 2011 and 45 GW by the end of 2018, contributing with more than 7% in net electricity share (ISE, 2019). China achieved 100% electrification from PV systems installed since 2012. In 2017, for the first time, solar PV was China's leading source of new power capacity (nearly 53 GW). By the end of 2018, total installations approached 180 GW, far surpassing the Chinese government's minimum target of 105 GW for 2020 (SPE, 2019). The global solar PV sector reached a cumulative capacity of 245 GW in 2015 and increased to more than 600 GW in 2019 (IEA, 2019). A 1,100 GW of global PV power capacity could be reached by the end 2022 (ISE, 2019).

On the other hand, Libya is a rich country in RE resources; it has the potential to produce the equivalent of almost seven million barrels of crude oil per day in energy (Bindra et al., 2015) i.e., more than four times the pre-conflict daily oil production level (1.6 million barrel) (NOC, 2020). Solar energy in Libya is one of the highest solar irradiations in the world, referring to Fig. 4. The average annual solar irradiation is 2,470 kWh/m^2/year, whereas the potential of solar energy resource is estimated at 140 $\times$ 10^6 GWh/year (RCREEE, 2010). With its distinct geographical location and massive potential of solar energy, Libya is capable of providing

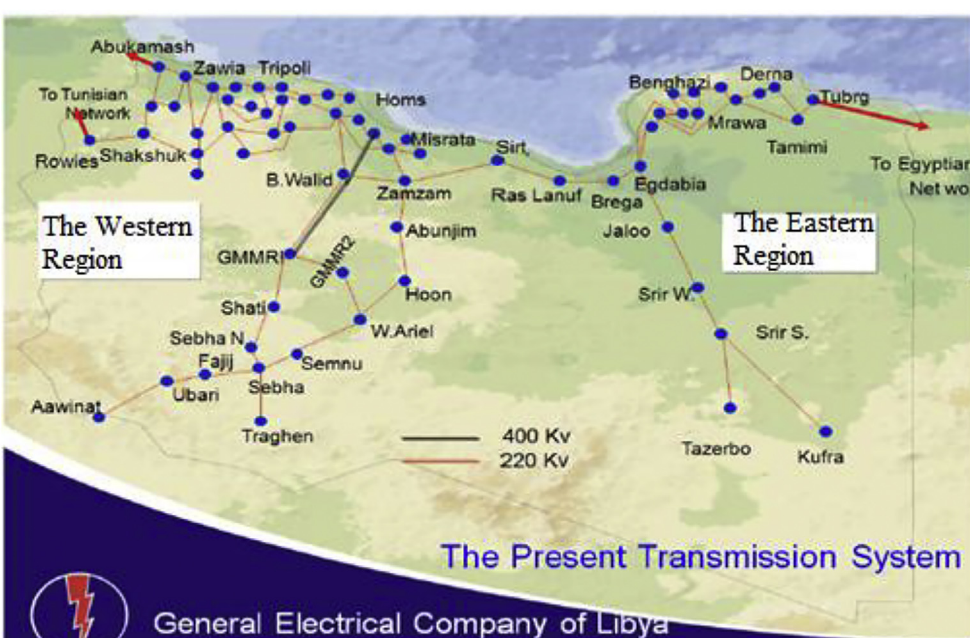


Fig. 3. Libyan national transmission grid (220 kV & 400 kV).

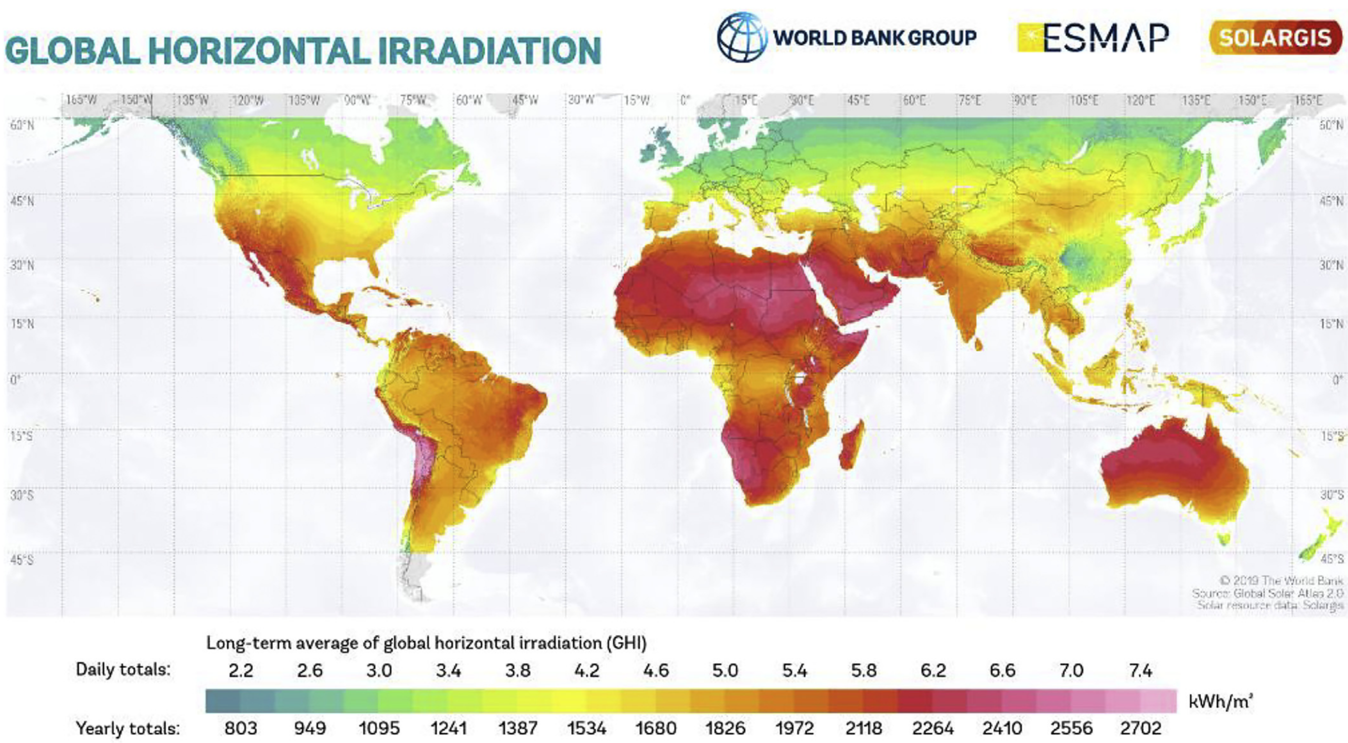


Fig. 4. Global horizontal irradiation (kWh/m^2/year) (SOLARGIS, 2019).

clean energy to Europe in the north and towards Africa in the south; where more than 500 million people in Sub-Saharan Africa live in darkness (Aly et al., 2019). Fig. 5 illustrates the monthly averaged insolation incidents on a horizontal surface in some selected Libyan cities (Aldali et al., 2011).

In the research prospect, techno-economic analysis of PV/wind/diesel/battery for powering Libyan schools was conducted (Glaisa et al., 2014). Alamry and Iqbal sized a standalone hybrid PV-wind-battery system for a house located in Tripoli (Alamri and Iqbal, 2016). The lowest levelized COE was obtained when the system was composed of 2.8 kW PV modules, 3 $\times$ 400 W wind generator and 56,200 Ah units of storage batteries. The potential of installing a 50 MW PV power plant in the southern region of Libya at Al Kufrah was evaluated (Aldali et al., 2011). The study concluded that the proposed plant can generate 114 GWh and reduce 76 thousand tonnes of CO_2 pollution per annum (Aldali, 2012). Performance of a PV water pumping system of 1.2 kW installed in Mrada, located in the Libyan desert, was evaluated. The results demonstrated that the technical and economic feasibility of using PV systems for water pumping, especially in remote areas, are guaranteed due to the high potential of solar insolation (Sbeta and Sasi, 2012). A study conducted by GECOL revealed that around 9.3% of the national electricity consumption in the country is consumed by water heating for domestic purposes (Ekhlat et al., 2009). Another study conducted by the CSERS concluded that replacing electric water heaters with solar water heaters in the Libyan residential sector will alleviate the electricity peak by 3% and the annual energy savings could reach up to 2.55 TWh (Abdunnabi et al., 2016).

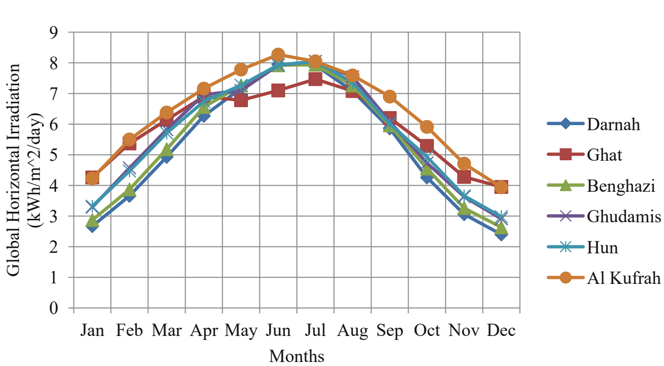


Fig. 5. Global horizontal irradiation for some selected Libyan Cities (kWh/m^2/day).

Historically, the use of PV technology in Libya dates back to the mid-seventies. Since then, several systems of different sizes and applications have been installed; such as cathodic protection, rural electrification, water pumping, and communications. The first project put into operation was a PV system to provide a cathodic protection for the oil pipeline connecting Dahra oil field with Sedra Port in 1976. The accumulated total power of PV systems in the field of cathodic protection was 650 kW from 320 systems installed until 2006. A PV system to supply energy to a microwave repeater station was built near Zella in 1980, while projects in the field of water pumping were started in 1983 (Sayah, 2017).

It was a successful experience technically and economically to replace all diesel stations with PV stations in the Libyan communication networks. The total number of PV powered stations in the field of telecommunications exceeding 120 stations with approximately 3 MW total installed capacity (Guwaeder and Ramakumar, 2017). The successful experience was based on the following criteria: no failure was experienced for the systems installed, no running cost, the average energy output was 6 kWh/day for systems of 1.2 kW. More than 400 systems have been installed for rural electrifications with 725 kW total peak power. The majority of standalone PV systems were installed by GECOL and CSERS (Saleh, 2006). While there are no official reports about the updated total installed PV capacity in Libya so far, however, it can be estimated at around 10–20 MW only, mostly as small residential systems.

Nevertheless, REAoL proposed a mid-term goal to reach 10% of the energy supply from RE resources by the year 2025. This would account for a total capacity of 2.22 GW. The plan included: 844 MW capacity of PV projects, 375 MW of concentrated solar power, 300 MW of solar water heating and 1,000 MW of wind farms. Examples of suspended projects are 14 MW PV power plant in Hun deep in the desert, 60 MW wind farm in Darnah and another 60 MW wind farm in Mesallata (REAoL, 2012). Other projects have been studied and proposed which include: 50 MW PV power plant in Shahat, 40 MW PV power plant in Sabha, 15 MW PV power plant in Ghat, 3 MW PV rooftop systems, 2 × 120 MW wind farms in Al Magroun (Bindra et al., 2015), (RCREEE, 2013). However, REAoL implementation plans were abruptly halted following the Libyan revolt in 2011.

Although there is an organization in Libya responsible for the promotion of RE, namely REAoL, the development of tools and mechanisms to promote RE sources is still lacking and existing ones are largely ineffective. Furthermore, to our best knowledge so far no one has analyzed the possibility of FiT implementation in Libya and hence the viability of solar PV energy. Therefore, one of the objectives of this work is to investigate the role of FiT to boost and expand the application of PV systems for the Libyan end users as a solution to the electricity shortage. Public-private partnership and private financing would then be sought.

Most of the reported realization of solar energy initiatives were carried out at the central government level, represented by REAoL, whether for small-scale applications or large-scale ones. With people experiencing regular long hours of power cuts and gas shortages, crumbled government agencies in Libya do not have the luxury, anymore, of diversifying energy resources to introduce RE in the generation mix. In fact, GECOL is currently struggling to tackle power outages using rotational load shedding, also known as rolling blackouts, with the aim of implementing an equitable and fair load shedding policy to all customers throughout the day. The misery of load shedding was further intensified very recently amid the quarantine caused by COVID-19 pandemic, due to the substantial increase in the residential load demand. In the absence of a unified government, collapsing infrastructure and worsening security, it is imprudent to count on government initiatives to provide solutions, which can be ultimately available via damaged or vulnerable grid of traditional “wires”. It is, therefore, imperative for local communities in Libya to tap the vast RE potential the country has and develop modular power supply via distributed renewable generation as a NWA connected directly to load centers.

4. Non-transmission solution using solar PV energy

The deteriorating security situation in Libya has rendered GECOL to be almost dysfunctional. Though GECOL’s national workforce undertakes repairs and maintenance works with what is available, the company is still handicapped from carrying out major routine overhauls or rehabilitation of damaged critical power system infrastructure; let alone system upgrades. This is due mainly to the lack of spare parts of the generating units. To make matters worse, international contractors have fled the country. This, consequently, has left significant portion of the Libyan population groaning under rolling blackouts for long hours daily. Whereas the people of Libya have resorted to using diesel generators that can be heard humming in the streets, fuel shortages and, occasionally, cuts are prohibiting ordinary people from ensuring a safe fuel supply. A renewable NWA could provide a more sustainable and secure solution to such problem.

NWA is defined as: “an electricity grid investment or project that uses non-traditional T&D solutions, such as DG, energy efficiency, demand response, and grid software and controls, to defer or replace the need for specific equipment upgrades, such as T&D lines or transformers, by reducing load at a substation or circuit level (Wikler et al., 2018). ESS is also proposed as part of the NWA to defer distribution capacity investments, while considering the physical model of the distribution feeders (Deboever et al., 2018).

NWA is considered by utilities as an additional location-specific option as opposed to traditional T&D investment. Utilities must conduct granular data analysis at the feeder level to understand the characteristics and demographics of the localized customers, hourly load shapes, technical potential of DG uptake, saturation level of renewable DG, and the propensity of adopting available DG resources with different technologies for alignment with the local load. Screening is then carried out to check whether the NWA is less costly than the traditional solution as well as NWA capability to provide firm capacity and sufficient reliability as compared to the traditional T&D solution. According to Federal Energy Regulatory Commission (FERC) order No. 1000 (Contreras-Ocaña et al., 2018), and US Department of Energy (DOE), by employing a comprehensive NWA approach customer can achieve the following benefits:

(i) Avoid unnecessary construction;
(ii) Best prioritize the use of capital for construction;
(iii) Minimize the risk of stranded investment;
(iv) Enhance capacity of existing systems through detailed analysis;
(v) Avoid unnecessary transmission cost increases; and
(vi) Minimize environmental impacts of transmission enhancements.

Renewable DG/ESS, serving as NWA, can be clustered to form small communities i.e., MGs. To achieve the highest system reliability and efficiency of the MGs, a proper power management and control scheme particularly under abnormal conditions of power system is critical (Bui et al., 2018; Çelik and Meral, 2019a, 2019b; Jayachandran and Ravi, 2019; Meral and Çelík, 2019; Rahman and Oo, 2017). While NWA is employed primarily to defer or avoid the cost of network upgrades and capacity expansion, it may be contemplated from a different perspective in the case of Libya. Given the current circumstances, there is no good reason to rely on GECOL for energy provision merely because it is mandated to do so. The blunt fact is the incumbent transmission provider, GECOL, cannot meet the reliability needs and service obligations.

As the country is already ravaged by civil war with damaged critical system infrastructure, an “ad-hoc” option to provide a regional solution could be the only practical alternative in the immediate and short-term to meet existing energy demand. Solar energy based DGs provide a reliable substitute which is more efficient, cost-effective, and fast-to-construct. Initially the investment and installation costs of solar DG, as a NWA, can be borne by local loads within the region. It can be connected to the grid at a later stage, when the security situation improves. A policy mechanism such as FiT can be used then to remunerate solar DGs for the energy injected into GECOL electricity grid.

5. Feed-in-tariff policy

FiT is defined as a policy initiative that encourages investment in RE by providing green power producers long-run assured purchase contracts to sell their electricity to the grid at a premium rate. Among existing policy mechanisms to accelerate the deployment of clean energy, FiT policies are the most widely implemented, and have proven to be the most promising, accounting for a greater share of RE dispersion than any other policy support scheme (Pyrgou et al., 2016).

The successful FiT system of Germany and Spain is worth a

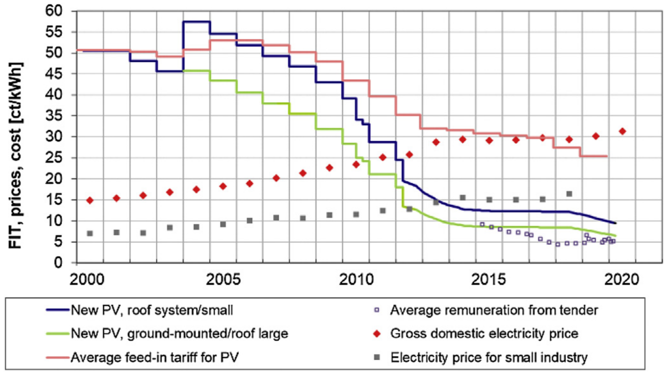


Fig. 6. Feed-in Tariff for PV technology and electricity prices in Germany (Fraunhofer, 2020).

study. Since 2008, as the FiT had been widely adopted stimulating the deployment of PV installations, costs of PV system components declined sharply. PV module prices fell nearly 40% in 2008 alone resulting in revisions of FiT in 2009, 2011, and lastly 2012 (Dusonchet and Telaretti, 2010). Fig. 6 depicts the history of the FiT in Germany until 2020. It is obvious that electricity from small-scale PV systems achieved the grid parity in 2012. It is also seen that average FiT for different PV capacities equated to the gross domestic electricity price in 2017. Since 2017, only rooftop systems are still eligible for FiT, while new plants with a rated output of more than 750 kW can only partake in calls for tender. After 2020, the FiT in Germany will gradually expire for the oldest plants, as their 20-year payment period is reached. However, these plants will continue to supply power at levelized costs that undercut those of all other fossil fuel and RE sources, due to low operating costs and zero fuel costs (Fraunhofer, 2020; Hoppmann et al., 2014). The 2008 Spanish FiT for installations ≤100 kW was set at 595% of the Reference Average Tariff (RAT) and the annual degression rate was capped at 10% (Dusonchet and Telaretti, 2010).

Meanwhile, China and Malaysia, as fast-developing countries, are examples of recent experiences that attained rapid remarkable results. FiT in China was initiated in 2011 to promote the adoption of solar PV technology, and have led to a substantial expansion especially in the PV domestic market. For early stage installations, the FiT started at 1.15 CNY/kWh (~18 $¢/kWh) and was set at an average of 0.92 CNY/kWh (~14 $¢/kWh) in its last adjustment in 2016, comparing to around 0.3 CNY/kWh (~5 $¢/kWh) for coal-fired electricity (Ye et al., 2017). Prior to the establishment of the Malaysian FiT policy in 2010, the incentives in the PV projects were in the form of capital grants (Wong et al., 2015). Table 2 summarizes the FiT since 2012, the year in which the first FiT was implemented, valid for 21 years (Chua et al., 2011). The Malaysian FiT was initially set at 0.4 $/kWh (1.23 RM/kWh) for systems less than 4 kW compared to 8 $¢/kWh (5 times) for base electricity tariff.

African governments also intend to increase the share of renewable energies in the power mix through FiT policy (Meyer-Renschhausen, 2013). Algeria was the first African country that had introduced FiT scheme in 2004. Solar-based electricity receives a premium rate at 300% of the electricity retail market price (Eberhard and Kaberger, 2016). Egypt is another example of developing countries that share similar climate and geopolitical disposition to Libya. The Government of Egypt represented by the Ministry of Electricity and Renewable Energy (MoERE) has adopted a FiT scheme since November 2014. The scheme aims to support investment in RE by setting a target of 4,300 MW in the first regulatory period. The purchase price for residential solar generation is 0.848 EGP/kWh (~12 $¢/kWh) while for non-residential installations of less than 200 kW of installed generation capacity, the price rises to 0.901 EGP/kWh (~13 $¢/kWh). The lifespan of the solar projects has been set at 25 years (Al-Ezzi, 2017). South Africa's Renewable Energy Independent Power Producer Procurement Program (REIPPPP) has run four competitive tenders/auctions since 2011. These were successful to reduce electricity prices of solar PV by 71%, reaching the grid parity. Over the four bidding rounds, $19 B has been invested in 92 RE projects totaling 6,327 MW (Eberhard and Kaberger, 2016).

As addressed earlier, the FiT is lowered over time as a result of technology maturity. The continuous development of PV technology has, in turn, led to a reduction in the PV module cost (Reichelstein and Yorston, 2013). According to Hanwha Q Cells, the average selling price, excluding the processing services, decreased from 1.24 $/W in 2011 to 0.67 $/W in 2012 (Hanwha, 2019). The cost of PV modules fell by 80% between 2009 and 2017 and 50% over the last four years, with current average price of around 0.3 $/W (Fraunhofer, 2020; Labordena et al., 2017). Due to economies of scale and technology improvements, with every doubling of cumulative installed capacity solar PV module prices drop by 20%. In 2017, 2.42 $¢/kWh have been granted for 350 MW solar PV park auction in Abu Dhabi (IRENA, 2017). In February 2019, a 900 MW tender in Dubai was granted at a new world record-breaking solar PV power price of 1.695 $¢/kWh (GoD, 2019). Typical levelized COE by PV technology is in the range 3 $¢/kWh by the end of 2019 (Bablo, 2018).

The model of the PV system proposed in this paper, to cater for the emergency needs of the Libyan people, adopts private financing or public-private partnership to provide quick cash and fast-to-construct renewable solar DGs at localized regions as a NWA, to GECOL electric energy provision system. In this vein, FiT is a suitable policy mechanism for local PV DGs to recover their investment cost plus a reasonable profit. FiT is an efficient tool to compensate solar DGs acting as a NWA to outsource GECOL internalized generation and T&D assets, due to the delimited capabilities of GECOL under the given energy crisis in Libya.

6. Case study

An electricity bill containing an average daily energy consumption of a typical house in Benghazi, Eastern Libya is obtained

Table 2
History of Feed-in Tariff in Malaysia in US dollar (Wong et al., 2015).

Year	FiT ($)		Bonus ($) (one or more)	
	Capacity ≤ 4 kW	4 kW ≤ Capacity≤24 kW	Use as installation in building structure	Use of locally manufactured or assembled solar PV modules
2012	0.40	0.39	+0.084	+0.016
2013	0.36	0.35	+0.076	+0.016
2014	0.318	0.31	+0.067	+0.015
2015	0.236	0.23	+0.050	+0.013
2017	0.171	0.167	+0.032	+0.011
2019	0.150	0.147	+0.028	+0.011

from the Power Distribution Sector of GECOL, is listed in Table 3. The energy consumption is based on an average energy consumption of 219 days of the year 2015. The daily energy load profile is depicted in Fig. 7. As can be seen, the peak energy demand occurs between 03:00 p.m. and 10:00 p.m. with an average peak of 2.4 kW.

One of the most important factors affecting the power output of a PV system is the amount of solar irradiation falling on a tilted surface at a particular location (Kapumpa and Virdi, 2016). The angle of the solar panel depends on the latitude of the site (Foster et al., 2010); therefore, latitude of Benghazi is the best tilt angle for a fixed solar panel to receive the maximum irradiation. However, to maximize the captured solar energy, the slope of the panel (β) can be changeable, as expressed by (1).

$$\beta = \begin{Bmatrix} \varphi - \delta & for \delta > 0 \\ \varphi & for \delta = 0 \\ \varphi + |\delta| & for \delta < 0 \end{Bmatrix} \quad (1)$$

where φ is the latitude of the site, δ is the declination angle, $-23.45^\circ < \delta < 23.45^\circ$. The optimal condition requires β to be changing daily throughout the year; however, it is more economical to mount the modules with only two adjustable angles throughout the year. Based on (1), it is recommended to adjust the tilt angle down to 17° in summer, i.e., April-August, and to 47° in winter, i.e., October-February. As obtained from NASA (NASA, 2019), this will lead to an increase in the average solar energy falling on the installed solar array by 5% to become 6.06 kWh/m^2/day in comparison to 5.78 kWh/m^2/day which was obtained when the system is fixed at 32°. This is demonstrated in Fig. 8 where more solar energy amount is captured when the solar system is tilted at 47° in winter and 17° in summer. This is advantageous for PV system investment both technically and economically.

According to (2) (Almaktar, 2015), the NWA PV system capacity which satisfies the house demand is found to be 5 kW, i.e., 20 panels of 250 W PV module.

Table 3
The average daily energy consumption for a typical house in Benghazi.

Period from	Period to	Number of days	Energy consumption (kWh)
05/02/2015	09/05/2015	93	1865
09/05/2015	10/06/2015	32	649
10/06/2015	18/08/2015	69	1372
18/08/2015	12/09/2015	25	497
Total		219	4383
The average of energy consumption (kWh/day)			**20**

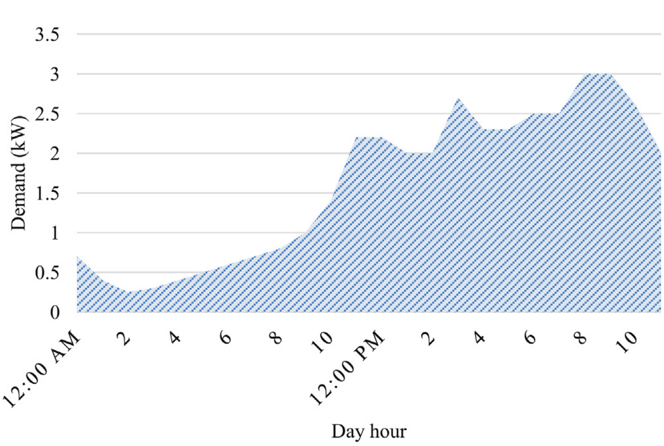


Fig. 7. Daily energy load profile of a typical house in Benghazi.

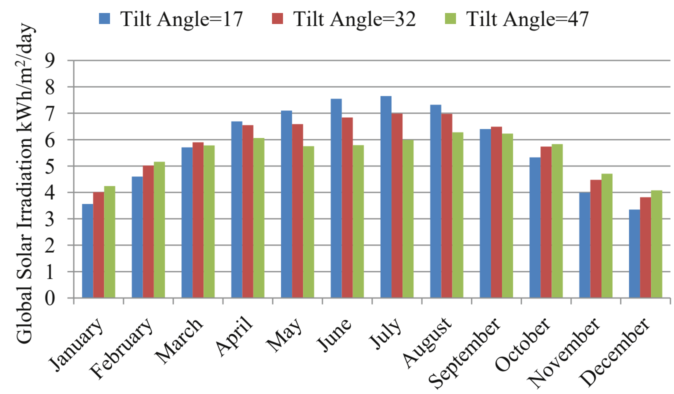


Fig. 8. Global solar irradiation received by a PV system at various tilt angles.

$$\text{PV System Capacity (kW)} = \text{Load (kWh)} / (\text{PSH} \times \text{System Losses}) \quad (2)$$

where PSH is the Peak Sun Hour in kWh/m^2/day; for Benghazi it is 5.78. Losses of the designed PV system must be considered to ensure that the system will feed the load effectively. The system efficiency was estimated as 71% including the inverter efficiency, PV module mismatch, losses in the DC and AC wires, soiling, and losses due to the PV module temperature increase (Liu et al., 2017).

7. Economic analysis model of the NWA solar PV based power system

The merit of the NWA 5 kW PV system is to provide an independent sustainable energy source to residential areas that is not reliant on intermittent power supply provided by GECOL; due to its damaged T&D infrastructure. The excess energy can also be exchanged in the local community to fulfill another end user energy need within a MG context. If the local distribution networks are upgraded, and political stability is largely restored, the excess clean energy from the PV systems can be sold back to the grid under the FiT policy.

The specification and cost breakdown for the different components used in this study are listed in Table 4. HOMER is utilized to investigate the feasibility of different hybrid energy systems to fulfil the energy requirement of the house under study. HOMER (HOMER, 2019) is basically an optimization software package that simulates various energy systems, including RE sources, configurations and sorts them on the basis of NPC and the levelized COE. NPC represents the life cycle cost of the system, i.e., the total cost of installing and operating the system over its lifetime, whereas the levelized COE is the average cost per kWh of useful electrical energy produced by the system.

On the other hand, NPV is a standard method for using the time value of money to appraise long-term projects. It compares the present value of money today to the present value of money in the future, taking into account the inflation and returns. The decision making on the investment depends on the value of NPV. If NPV >0, the investment would add value and the project may be accepted. If NPV <0, it means that the investment would incur losses and then the project should be rejected. On the other hand, if NPV = 0, the investment would neither gain nor loose value for the investor. The project adds no monetary value and the investor should be indifferent in the decision, whether to accept or reject the project. In this case, a decision should be based on other criteria (Jain, 1999).

The NPV can be calculated as (Bernal-Agustín and Dufo-López, 2006):

Table 4
Technical and economical characteristics of various components.

Component	Data description
Photovoltaic modules	
Technology	Polycrystalline, 250W
Capacity (kW)	5
Capital cost ($) including mounting, wiring, installation and commissioning	4,680
Operation and maintenance cost ($)	0
Replacement cost ($)	0
Working life (yr)	25
Derating factor (%)	90
System productivity (%)	80
System	Fixed
Power Convertor	
Type	Grid-tied, 1-ϕ, 220V, 50 Hz
Capacity (kW)	5
Capital cost ($)	2,000
Operation and maintenance cost ($)	0
Replacement cost ($)	1,700
lifetime (yr)	15
Efficiency (%)	95
Storage Battery	
Technology	Lead-acid
Nominal capacity (kWh)	1
Nominal voltage	12
Unit price ($)	250
Replacement cost ($)	200
O&M cost ($/yr)	50
Roundtrip efficiency (%)	80
Minimum state of charge (%)	30
Lifespan (yr)	11
Diesel Generator	
Capacity (kW)	5
Capital cost ($)	1,000
Operation and maintenance cost ($/hr)	0.03
Replacement cost ($)	800
Runtime (hr)	10,000

$$NPV = -S + \frac{Q_1}{(1+i)} + \frac{Q_2}{(1+i)^2} + \ldots\ldots + \frac{Q_N}{(1+i)^N} = -S + \sum_{j=1}^{N} \frac{Q_j}{(1+i)^j} \tag{3}$$

Where i is the nominal interest rate. NPV should be as large as possible and always positive so that the generated benefits are greater than costs.

The initial cost (S) of the GCPV (without battery storage) system can be expressed as:

$$S = C_{gen} + C_{inv} + C_{inst} - C_{incn} = C_{system} - C_{incn} \tag{4}$$

where C_{gen} is the cost of the NWA GCPV generator, C_{inv} is the cost of the inverter. C_{inst} is the cost of installation including supporting structures, wiring, protective elements, etc. C_{system} is referred to as system cost which is a total of PV generator cost, inverter cost, and installation cost, whereas Cincn is the sum of financial incentives on the initial cost. Usually governments and their affiliated agencies provide financial incentives to RE projects to promote their wider adoption. These incentives could be in the form of grants for supporting capital investment, loan programs, tax credits, and the like. While one or more incentives can be obtained, it is assumed that these incentives can be lumped in a single component for simplicity.

Q_j is the difference between the cash input generated by the investment and the payment (cash output) the investment requires for a certain period in time (year j). The Net Cash Flow for a year j is expressed as;

$$Q_j = (\text{Cash input})_j - (\text{Cash output})_j = (p_b \cdot E_{PVaut} + P_s \cdot E_{PVinj}) - (C_{O\&M} + C_{ins} + C_{Fin}) \tag{5}$$

where p_b and p_s are the energy bought from and sold to the national utility grid, respectively. E_{PVaut} is the auto-consumed (not bought from the grid) annual energy generated by the NWA PV system connected to the grid. E_{PVinj} is the annual energy generated from the PV system injected into the utility grid. $C_{O\&M}$, C_{ins} and C_{Fin} are attributed to the annual costs of operation and maintenance, insurance, and financing, respectively.

It is assumed that no limitation is imposed for the amount of energy generated by the NWA fed into the utility grid i.e., all the produced energy can be sold which is, therefore, the most favorable situation for the PV installer. Thus, $E_{PVaut} = 0$. The annual operation and maintenance cost $C_{O\&M}$ of the system installed was taken as 2% of the initial cost S (Rahman, 2012). Also, C_{ins} and C_{Fin} are assumed to be zero in the sense that there is no insurance or financing costs for the PV system installed. Furthermore, $C_{O\&M}$ increases with inflation (g); therefore, equation (5) becomes;

$$Q_j = (p_s . E_{PVinj}) - (C_{O\&M} * (1+g)^i) \tag{6}$$

Energy prices are highly subsidized in Libya, in which fuel prices are among the lowest in the world. Expenditure on fuels and electricity subsidies are equivalent to more than 11% of GDP (Richard et al., 2014). The current base price of domestic electricity and diesel fuel is 0.02 LD/kWh (~1.4 $¢/kWh) and 0.15 LD per liter (~0.11 $/L) respectively. In fact, the cost of fuel is not stable and could increase. In October 2019 the Libyan government raised commercial price of kerosene from 0.15 LD (~0.11 $), to 0.85 LD (~0.6 $) (AUE, 2017). The price of other fuel types is also expected to be raised in the near future. Contrarily, in comparison with the Libyan case, international experience of electricity tariff structure show that the electricity price ranges between 10 and 20 $¢/kWh (IEA, 2012).

On the other hand, the inflation rate in Libya had a serious hike to 28% during 2017, compared to only 2.4% in 2014. As oil production and exports improved, associated with relatively high international price, the inflation rate decreased again at an average of 13% during 2018. Fig. 9 depicts the fluctuation of inflation since 2008 as provided by the CBL (CBL, 2018).

Inflation rate was affected by a drastic drop in oil revenues, the main national income source, from $53 B and $41 B in 2012 and

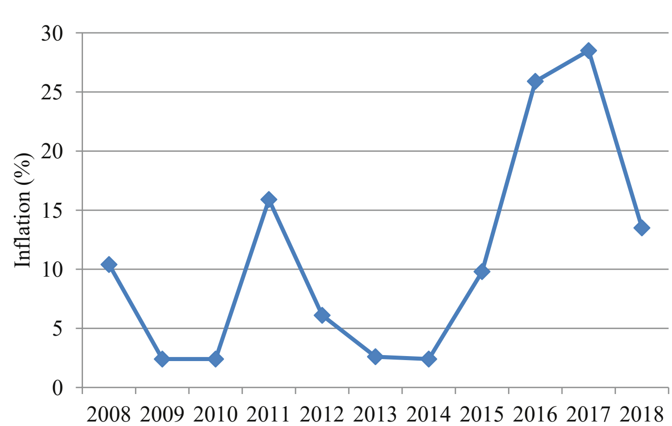


Fig. 9. Inflation rate in Libya during 2008–2018 (CBL, 2018).

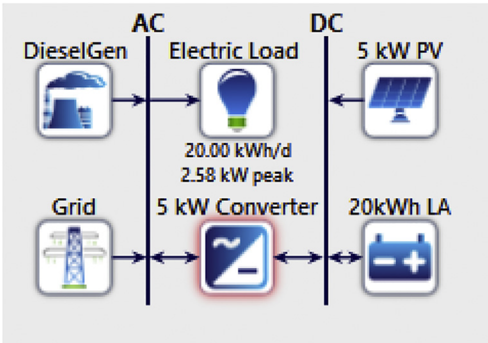


Fig. 10. Hybrid energy model for the house under study.

2013 in comparison to just $16 B and $8 B in 2014 and 2015 respectively. In 2016, the oil revenue fell dramatically further to only $2 B in the first half of the year (CBL, 2018). This is mainly due to the political crisis in the country as well as the absence of security in most of the large oil fields and ports.

8. Results and discussion

8.1. HOMER simulation

With the aim of ensuring continuous electricity supply during blackouts and scheduled shutdowns, the study first considers a hybrid energy system. A combination of PV, diesel generator, battery storage, representing a NWA solution, with grid connection option has been considered. The schematic diagram of the hybrid system model is depicted in Fig. 10.

The investigation is focused on the analysis of several scenarios of battery amperage capacity, diesel generator fuel price, electricity tariff, and inflation rate. In terms of energy sale, the study initially assumes that the NWA system receives no incentive for injecting excess energy into the grid as this is the real case currently in Libya. The variables are simulated as follows: grid electricity rate [1.4, 10] $¢/kWh, battery bank storage capacity [5, 14, 25] kWh, diesel fuel price [0.11, 0.6, 1.0] $/L, and inflation rate [2, 6, 12]%. Thus 10,266 solutions were simulated.

Considering the grid electricity price equals to 1.4 $¢/kWh (current tariff), inflation rate at 12%, diesel fuel price in its lowest (11 $¢/L), and $0 for the price of energy sold back to the grid, it is found that the optimum configuration is for the PV-grid without battery storage, referring to Fig. 11. This scenario offers the least NPC and COE with $7,172 and 2.51 $¢/kWh respectively, as depicted in Fig. 12 showing the electrical simulation results of the system. As can be noticed, although the grid energy price is at the lowest tariff, yet the PV system covers 66% of the load demand. This system can yield an excess annual energy of 4,187 kWh that can later be sold to end users in the local communities.[1]

The second optimal scenario is when adding 2 kWh battery bank to the previous combination with a COE of 2.91 $¢/kWh. It is clear from the results that the system cost is affected primarily by the low grid tariff and addition of the ESS. The option of adding 20 kWh of battery bank to the PV NWA, without grid connection, would result in a NPC of $30,838 and a COE of 8.5 $¢/kWh. This is obvious from the cash flow results, shown in Fig. 13, where the ESS of 20 battery units comprises 58.4% of the total system NPC.

Even at the lowest price of grid power and diesel fuel, the diesel generator alone option offers the most expensive electricity cost option and the highest NPC. The resultant NPC and COE of the NWA, diesel only option, are $46,437 and 19.8 $¢/kWh respectively as summarized in Fig. 14. This is mainly due to the high expenses attributed to its operation and replacement costs. Furthermore, under low-load levels, and due to the combustion characteristics of the diesel fuel, the emissions increase substantially. In this case the diesel generator becomes inefficient, leading ultimately to an increase in its O&M costs.

At a higher grid power price, i.e., 0.1 $/kWh, diesel fuel price of 0.11 $/L, the most economic combination of the diesel-grid option is when only 16.2% comes from the diesel generator and the remaining is imported from the grid. The resultant NPC and COE for the latter option is $24,560 and 10 $¢/kWh compared to $19,000 and 6 $¢/kWh for the 67.5%–32.5% PV-grid option. At a grid power price of 0.1 $/kWh, diesel price of 0.6 $/L, the combination of PV-grid (60% renewable fraction) without the ESS is still the best option with NPC and COE of $19,700 and 5.9 $¢/kWh respectively.

Simulation results have shown that a higher diesel fuel price leads to an increase in the total cost of the system which in turn increases the COE. In addition of being uneconomical, with excessive emission contribution to the environment, as well as sensitivity to fuel price, using diesel generator as a NWA also affects the people's comfort in terms of air quality and noise, especially in a condensed populated area such as Benghazi. On top of that, diesel as a fuel may not be always available due the sporadic fighting and security situation in townships of Libya. Fig. 15 demonstrates the advantages of utilizing the PV-grid option in offering less pollutant energy.

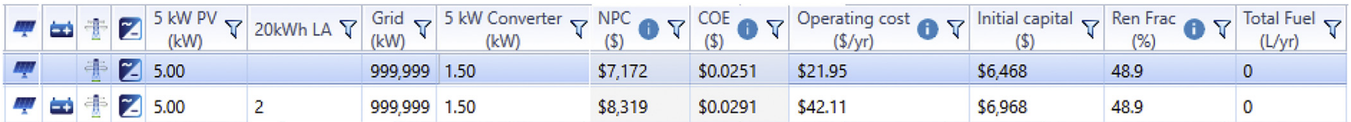
It is worthwhile to point out to some important observations and recommendations herein:

- ESS is a key factor for utilizing the PV based NWA system and it is also the dominant factor impacting the total cost. For this reason, it is necessary to decrease the size of battery bank by changing people's attitude of utilizing electrical energy. Shifting the evening peak load to day hours, as shown in Fig. 7, would significantly help the wider implementation of cost-effective NWA PV systems.
- As a greater number of NWA systems proliferate, renewable DG based MGs are formed. As such, an efficient control and power management strategy is required, considering the abnormal condition and characteristics of the Libyan power system, for optimal power exchange in islanded/grid interface MGs.
- Removing the subsidy on conventional fuel price, particularly diesel and gasoline, plays a critical role in stimulating the Libyan people to switch to RE systems. After all, people always respond to technologies that provide monetary savings to them.
- As soon as the national electric power grid recovers and its operations assume normalcy, reviewing the heavily subsidized electricity tariff in Libya should be among the first priorities. This is a critical issue to the applicability of FiT mechanism.

8.2. Analysis based on NPV and pay-back time

It is evident from the preceding results that the PV-battery-grid

[1] It is assumed that the PV system would be connected as DG to one of the laterals of a radial feeder in the LV distribution system. These laterals may be single-phase, two-phase, or three-phase. The radial distribution system is the dominant configuration in the suburban areas of eastern and western Libya. It is plausible that few house connections, with the PV system, to a lateral could form a MG that can be managed to provide energy to other houses/MGs that experience an energy shortage, in return for an agreed consumption fees. This may enable PV system owners to recover part of their costs in the immediate/short term as well as providing other neighbor dwellers with home-grown constant energy supply; away from the complexities associated with centralized GECOL energy provision infrastructure.



5 kW PV (kW)	20kWh LA	Grid (kW)	5 kW Converter (kW)	NPC ($)	COE ($)	Operating cost ($/yr)	Initial capital ($)	Ren Frac (%)	Total Fuel (L/yr)
5.00		999,999	1.50	$7,172	$0.0251	$21.95	$6,468	48.9	0
5.00	2	999,999	1.50	$8,319	$0.0291	$42.11	$6,968	48.9	0

Fig. 11. Optimization results for the hybrid energy system.

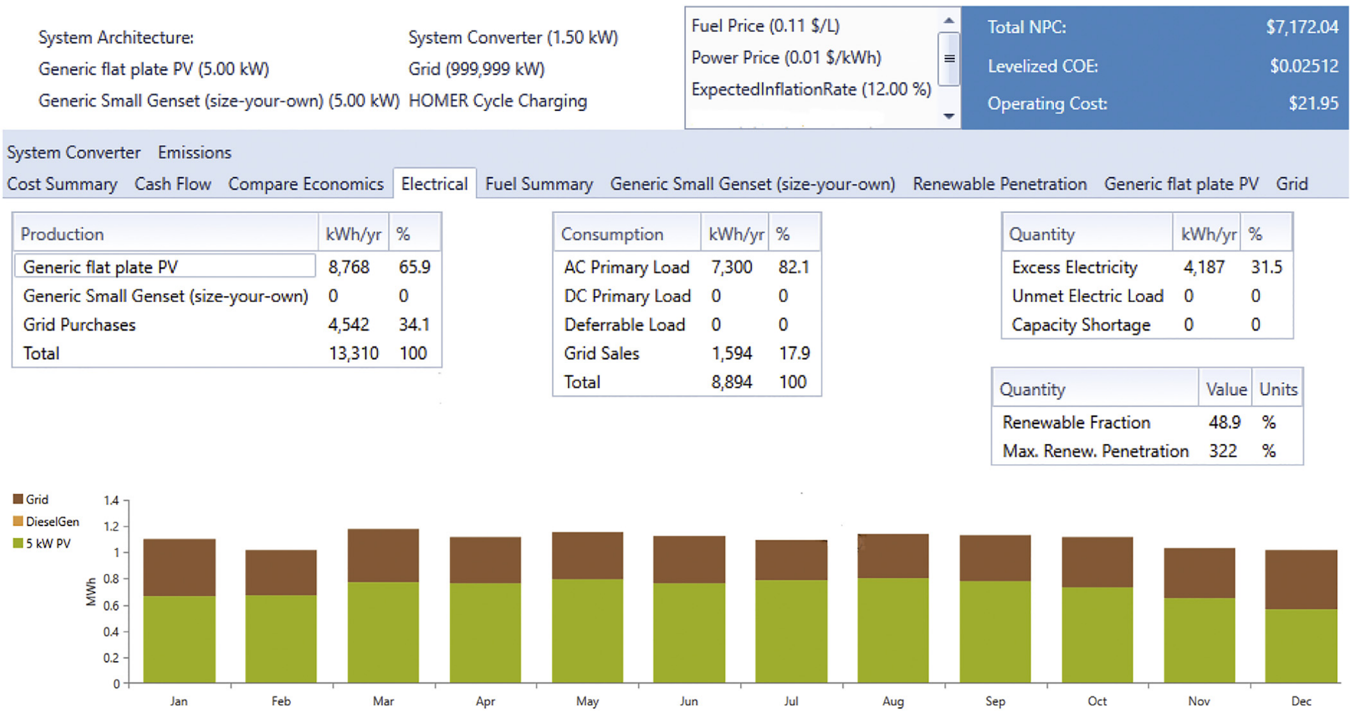


Fig. 12. Electrical simulation results for the base case scenario.

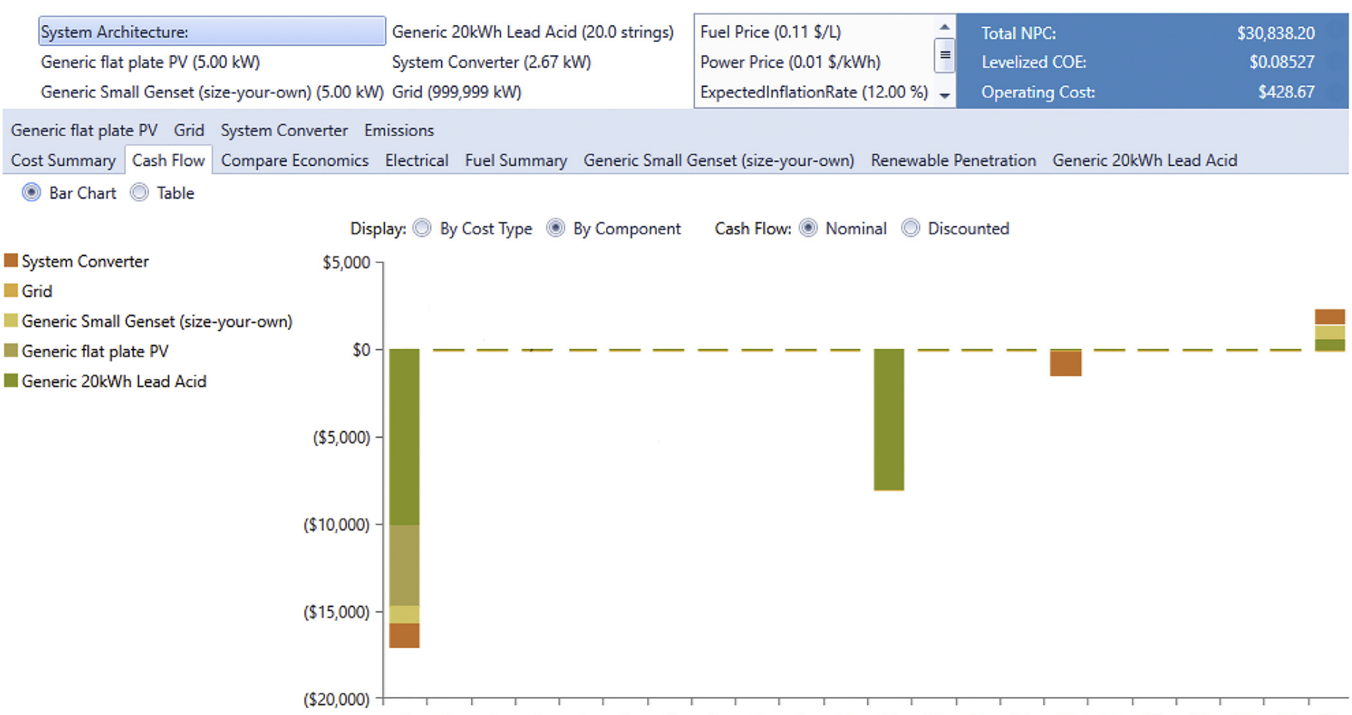


Fig. 13. Cash flow for 5 kW PV-20 kWh battery NWA system at base scenario.

System Architecture:
Generic Small Genset (size-your-own) (5.00 kW)
HOMER Load Following

Fuel Price (0.11 $/L)	
ExpectedInflationRate (12.00 %)	
Total NPC:	$46,437.67
Levelized COE:	$0.1982
Operating Cost:	$1,415.73

Cost Summary | Cash Flow | Compare Economics | Electrical | Fuel Summary | Generic Small Genset (size-your-own) | Emissions

Production	kWh/yr	%
Generic Small Genset (size-your-own)	11,492	100
Total	11,492	100

Consumption	kWh/yr	%
AC Primary Load	7,300	100
DC Primary Load	0	0
Deferrable Load	0	0
Total	7,300	100

Quantity	kWh/yr	%
Excess Electricity	4,192	36.5
Unmet Electric Load	0	0
Capacity Shortage	0	0

Quantity	Value	Units
Renewable Fraction	0	%
Max. Renew. Penetration	0	%

Fig. 14. Electricity production of the NWA diesel-only option.

Diesel only

Quantity	Value	Units
Carbon Dioxide	11,997	kg/yr
Carbon Monoxide	74.9	kg/yr
Unburned Hydrocarbons	3.30	kg/yr
Particulate Matter	0.449	kg/yr
Sulfur Dioxide	29.4	kg/yr
Nitrogen Oxides	70.4	kg/yr

Diesel-grid

Quantity	Value	Units
Carbon Dioxide	5,230	kg/yr
Carbon Monoxide	7.68	kg/yr
Unburned Hydrocarbons	0.338	kg/yr
Particulate Matter	0.0460	kg/yr
Sulfur Dioxide	20.4	kg/yr
Nitrogen Oxides	15.7	kg/yr

grid only

Quantity	Value	Units
Carbon Dioxide	4,614	kg/yr
Carbon Monoxide	0	kg/yr
Unburned Hydrocarbons	0	kg/yr
Particulate Matter	0	kg/yr
Sulfur Dioxide	20.0	kg/yr
Nitrogen Oxides	9.78	kg/yr

PV-grid

Quantity	Value	Units
Carbon Dioxide	2,870	kg/yr
Carbon Monoxide	0	kg/yr
Unburned Hydrocarbons	0	kg/yr
Particulate Matter	0	kg/yr
Sulfur Dioxide	12.4	kg/yr
Nitrogen Oxides	6.09	kg/yr

Fig. 15. Comparison of the GHG and other pollutants between the investigated systems.

hybrid power system is always feasible as compared to diesel only system for all price ranges of the diesel fuel considered. Whether a PV-grid or PV-battery-grid system, as part of being reliable in fulfilling the load demand, there will be always an opportunity for investment in selling back clean energy to the national high-voltage power grid when the war comes to an end.

The economic model of the GCPV system, described in section 7, was simulated using a developed Matlab code. Using the NPV and the payback period, a sensitivity analysis was conducted to investigate the effect of nominal interest rate, inflation, financial incentives, and FiT on investment feasibility for a 5 kW PV based NWA system with grid interaction. The programmed scheme imposes no limitation on energy sold, i.e., in this case the NWA system can, hypothetically, sell its entire energy production to the grid. Table 5 exhibits the feasibility results of the project considering the base price of electricity equals 1.4 $¢/kWh and FiT of 7 $¢/kWh with different scenarios of nominal interest rate, inflation, and fuel subsidies.

While FiT stands at a rate of five times higher than the base price of electricity, the investment remains unprofitable with negative NPV. For example, when the inflation rate is 2% and the project receives no financial incentives the NPV is $-1,399, i.e., at the end of the project lifetime the investment would lose $1,399. It is clear that the most favorable situation is when the financial incentive from the government amounts to 60% of the capital cost with 0% interest rate and 0% inflation. In this case, the net profit of the project is $5,358 and the investment returns its cost in 11 years. This corresponds to about $45 monthly revenue starting from the year 12 until the end of the contract lifetime. For higher interest rates and inflation, e.g., at 6% interest rate and 4% inflation, the investment is not viable unless 60% of the project investment costs are covered from the government. With the specified grid power price of 1.4 $¢/kWh and FiT of 7 $¢/kWh, at an inflation rate of 12%, the PV installation project is not feasible even when the project receives incentives up to 60% of capital cost, as shown in Table 6.

With such an inflation level, in order for the investment to be feasible, the FiT must be higher than 7 $¢/kWh. Table 7 presents the sensitivity analysis of the system when the electricity tariff remains at 1.4 $¢/kWh (subsidized rate), while the FiT is increased to 14 $¢/kWh. From the scenarios analyzed, it is found that for a positive NPV, the incentives must be at least 7% of the capital cost. With 20% incentives, the total profit earned at the end of the investment duration is $1,396, while the cost of the PV project would be at a breakeven on the year 13. It is unmistakably clear that the higher the financial incentives, the higher the NPV earned and the less the payback time needed. Nevertheless, with an inflation rate of 28%, the PV system project is unfeasible, and a new policy should be worked out.

To investigate the impact of using unsubsidized electricity tariff rate on the financial viability of the PV NWA system, the tariff rate and FiT are increased. As depicted in Table 8, the PV project is financially feasible, even with an unsubsidized tariff rate of 10 $¢/kWh, FiT as twice as the tariff rate, inflation of 12%, and 0% incentives. However, at an inflation rate of 28%, the 2017 rate in Libya, the sell-back price of electricity at 20 $¢/kWh is not profitable even with up to 60% incentives of the capital cost.

Table 9 provides the sensitivity analysis when the electricity tariff remains unsubsidized at 10 $¢/kWh, while the FiT is increased to 35 $¢/kWh. From the conducted feasibility study, it can be clearly observed that the higher the FiT, the more the profit earned and hence a lower payback time is guaranteed. For example, at $i = 0\%$, $g = 12\%$ and 0% incentive, the NPV was $33,100 with 7 years payback time (when FiT $= 0.35$ $/kWh) comparing to $10,630 revenue and 10 years payback period when the FiT equals to 0.2

Table 5
Sensitivity analysis of the 5 kW GCPV installation at electricity rate = 0.014 $/kWh and FiT = 0.07 $/kWh.

Nominal Interest Rate, *i* (%)	Inflation, *g* (%)	Incentives (%)	NPV ($)	Payback Period (Years)
0	0	0	−642	above 21
0	0	20	1,358	20
0	0	40	3,358	16
0	0	60	5,358	11
2	0	20	−420	above 21
2	0	40	1,580	18
2	0	60	3,580	12
0	2	0	−1,399	above 21
0	2	20	600	21
0	2	40	2,600	17
0	2	60	4,600	12
2	2	20	−990	above 21
2	2	40	1,010	20
2	2	60	3,010	13
4	2	20	−2,184	above 21
4	2	40	−184	above 21
4	2	60	1,815	14
4	4	20	−2,744	above 21
4	4	40	−744	above 21
4	4	60	1,255	15
6	4	20	−3,526	above 21
6	4	40	−1,526	above 21
6	4	60	473	19

Table 6
Sensitivity analysis of the 5 kW NWA System at FiT = 0.07 $/kWh and inflation rate = 12%.

i (%)	*g* (%)	Incentives (%)	NPV ($)	Payback Period (Years)
0	12	0	−10,714	above 21
0	12	20	−8,714	above 21
0	12	40	−6,714	above 21
0	12	60	−4,714	above 21

Table 7
Sensitivity analysis at FiT = 0.14 $/kWh.

i (%)	*g* (%)	Incentives (%)	NPV ($)	Payback Period (Years)
0	12	0	−603	above 21
0	12	20	1,396	13
0	12	40	3,396	10
0	12	60	5,396	7
0	28	60	−97,385	above 21

Table 8
Sensitivity analysis of the NWA at electricity rate = 0.1 $/kWh and FiT = 0.2 $/kWh.

i (%)	*g* (%)	Incentives (%)	NPV ($)	Payback Period (Years)
0	0	0	20,702	9
0	2	0	19,945	9
2	2	20	16,300	8
4	4	20	11,515	9
0	6	0	17,646	10
0	12	0	10,630	10
2	12	20	9,495	9
0	28	0	−92,157	above 21
0	28	60	−86,157	above 21

$/kWh. This undoubtedly would encourage end users to install their own solar PV systems, thus the reliability of electricity supply in local communities is assured.

The results detailed in Table 9, reiterates that at the highest inflation level (28%) the investment on PV technology in residential installations is not feasible even when the incentives to the PV projects reaches 60% of the capital cost. Finally, Table 10 analyzes the NPV and payback period of the 5 kW solar home at 28% inflation rate when the electricity is unsubsidized, with FiT increased to 70 $¢/kWh (~1.0 LD/kWh). The results acquired emphasize that at 28% inflation level the investment on PV technology is untenable even when the FiT is about seven times the base electricity price.

Table 9
Sensitivity analysis at electricity rate = 0.1 $/kWh and FiT = 0.35 $/kWh.

i (%)	*g* (%)	Incentives (%)	NPV ($)	Payback Period (Years)
0	0	0	43,170	6
0	2	0	42,413	6
2	2	20	34,501	6
4	4	20	26,525	6
0	6	0	40,115	6
0	12	0	33,100	7
0	28	0	−69,686	above 21
0	28	60	−63,686	above 21

Table 10
Sensitivity analysis at electricity rate = 0.1 $/kWh and FiT = 0.70 $/kWh.

i (%)	*g* (%)	Incentives (%)	NPV ($)	Payback Period (Years)
0	28	0	−13,515	above 21
0	28	60	−7,515	above 21

Whereas the inflation rate in Libya reached its peak in 2017 at 28%, it tumbled to 13% in 2018 and continued to decline to −1.16% in the first half of 2019 as a result of economic reforms adapted by CBL. However, it is expected to rebound afterwards because of the intensified conflict around Tripoli. With an inflation rate less than 12%, the PV grid system, as demonstrated in the results, is an attractive investment in Libya from the standpoint of financial viability.

9. Concluding remarks

As the political violence in Libya rumbles on for nine years now, the electrical power grid infrastructure is bogged down with frequent military incursions, rocket hits, sabotage and vandalism. This has severely undermined the grid capability of reliable power delivery, leading to exacerbated power cuts and leaving millions of Libyans groaning without electricity for long hours daily. As this timeless electricity crisis does not seem to have an immediate resolution in the horizon, restoring the reliability of power supply, at any cost, is critical to Libya's economic vitality and the well-being of the society.

Due to the proven vast potential of solar PV in Libya, this paper has espoused using small-scale PV systems in local communities, working as non-wires alternative (NWA) to utility grid, to close the energy provision shortfall in a decentralized manner. Increased PV based NWA systems can be configured in such a way to form clusters of well managed islanded microgrids (MGs). These standalone MGs can then be easily transformed to grid-interfaced MGs once the Libyan power system is stabilized. Various configurations of PV/battery/diesel generator hybrid systems with grid connection option were thoroughly explored under multiple scenarios of electricity tariff, fuel price, battery amperage capacity, inflation, interest rate, and government incentives. It is found that, under the current subsidized grid electricity price (1.4 $¢/kWh), inflation rate at 12%, current subsidized diesel fuel price (11 $¢/L), the most economic standalone NWA option goes to 5 kW-2 kWh PV-battery system yielding to 2.91 $¢/kWh of electricity cost. Whereas the incorporation of energy storage system (ESS) in the PV system increases the cost of energy (COE) and the net present value (NPV), utilizing renewable PV systems is more attractive financially than using the diesel generation option. Furthermore, the PV options come with security of supply, cleaner environmental footprint, and a greater societal benefit. The latter can be achieved not only from the continuous clean energy supply, but also by maintaining people's comfort via avoiding the noise accompanying gas-guzzling diesel generators in densely-populated townships in eastern and western Libya. For the NWA grid interfaced system, the most economic option is found to be PV-grid with 66% renewable fraction even at $0 for the sell-back price; this offers a COE and NPV of 2.51 $¢/kWh and $7,172 respectively. At a higher diesel price, the PV-battery option demonstrates its viability as the optimal standalone NWA solution.

Employing feed-in-tariff (FiT) in PV grid systems was extensively investigated as well, under assorted conditions of government financial incentives, pricing subsidies, inflation rates, and nominal interest rates. Increasing the FiT tends to lower the payback period, thus enhancing the financial viability of the PV grid system. On the other hand, doubling down on the incentives provided to RE projects would make it more financially appealing. Under unsubsidized pricing of electricity, the PV grid system exhibits attractive potential that supersedes the case of subsidized pricing. Nevertheless, results have consistently demonstrated that higher inflation rates are detrimental to the feasibility of the PV grid system, rendering the whole scheme to be futile. It is of paramount importance to keep inflation at bay to reap the full benefits of solar PV grid systems acting as a NWA in local communities. This can assist in restoring the reliability of electric energy supply as well as alleviating the lingering problem of electricity shortages in Libya.

While this study is primarily dedicated to the energy supply system in Libya, the arguments presented herein can be extended to countries ravaged by political instability, insurgency and regional conflicts in the Middle East such as Iraq, Syria and Yemen.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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